

Search for the  $b \rightarrow d\gamma$  process

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## Abstract

We report search results for the flavor-changing neutral current process  $b \rightarrow d\gamma$  with a data sample containing 274 million  $B$  meson pairs accumulated at the  $\Upsilon(4S)$  resonance with the Belle detector at KEKB. We studied the exclusive decays  $B^- \rightarrow \rho^-\gamma$ ,  $\overline{B}^0 \rightarrow \rho^0\gamma$ , and  $\overline{B}^0 \rightarrow \omega\gamma$ , and find no significant signal. We set an upper limit for a combined branching fraction  $\mathcal{B}(B \rightarrow (\rho, \omega)\gamma) < 1.4 \times 10^{-6}$  at the 90% confidence level, which is normalized to that of  $B^- \rightarrow \rho^-\gamma$  assuming an isospin relation between the three modes.

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The  $b \rightarrow d\gamma$  process, shown in Fig. 1(a), is a flavor changing neutral current transition that proceeds via loop diagrams in the Standard Model (SM). It is suppressed with respect to  $b \rightarrow s\gamma$  by the Cabibbo-Kobayashi-Maskawa (CKM) factor  $|V_{td}/V_{ts}|^2 \sim 0.04$  with a large uncertainty due to the lack of precise knowledge of  $V_{td}$ . The exclusive modes  $B \rightarrow \rho\gamma$  and  $\omega\gamma$ , which are presumably dominant, have not yet been observed [1, 2]. They are also suppressed with respect to the corresponding exclusive decay  $B \rightarrow K^*\gamma$  by  $|V_{td}/V_{ts}|^2$ , with corrections due to form factors,  $SU(3)$  breaking effects and the additional annihilation diagrams (Fig. 1(b)), giving predicted branching fractions in the range  $(0.9\text{--}2.7) \times 10^{-6}$  in the SM [3, 4]. Measurement of these exclusive branching fractions would improve the constraints on  $V_{td}$  in the context of the SM, and would provide sensitivity to physics beyond the SM that is complementary to that from  $b \rightarrow s\gamma$ .

In this paper, we report the results of a search for the  $b \rightarrow d\gamma$  process using a data sample of  $(274 \pm 3)$  million  $B$  meson pairs accumulated at the  $\Upsilon(4S)$  resonance. The data are produced in  $e^+e^-$  annihilation at the KEKB energy-asymmetric (3.5 on 8 GeV) collider [5] and collected with the Belle detector [6]. The Belle detector is a large-solid-angle spectrometer that includes a silicon vertex detector (SVD), a central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to identify muons (KLM). The dataset consists of two subsets with different inner detector configurations: for the first 152 million  $B$  meson pairs, a 2.0 cm radius beampipe and a 3-layer SVD were used; and for the remaining 122 million  $B$  meson pairs, a 1.5 cm radius beampipe, a 4-layer SVD and a small-cell inner drift chamber were used [7].

We reconstruct the following final states:  $B^- \rightarrow \rho^-\gamma$ ,  $\overline{B}^0 \rightarrow \rho^0\gamma$ , and  $\overline{B}^0 \rightarrow \omega\gamma$ . (Charge conjugate modes are implied throughout this paper.) We also reconstruct control samples of  $B^- \rightarrow K^{*-}\gamma$  and  $\overline{B}^0 \rightarrow \overline{K}^{*0}\gamma$  decays. The following decay chains are used to reconstruct the intermediate states:  $\rho^- \rightarrow \pi^-\pi^0$ ,  $\rho^0 \rightarrow \pi^+\pi^-$ ,  $\omega \rightarrow \pi^+\pi^-\pi^0$ ,  $K^{*-} \rightarrow K^-\pi^0$ ,  $\overline{K}^{*0} \rightarrow K^-\pi^+$ , and  $\pi^0 \rightarrow \gamma\gamma$ .

Photon candidates are reconstructed from isolated clusters in the ECL that have no corresponding charged track, and a shower shape that is consistent with that of a photon. The photon with the largest center-of-mass (CM) energy in the range  $1.4 \text{ GeV} < E_\gamma < 3.4 \text{ GeV}$  and in the barrel region of the ECL ( $33^\circ < \theta_\gamma < 128^\circ$  in the laboratory frame) is selected as the primary photon candidate. To suppress backgrounds from  $\pi^0 \rightarrow \gamma\gamma$  and  $\eta \rightarrow \gamma\gamma$  decays, we veto the event if the reconstructed mass of the primary photon and any other photon of 30 (200) MeV or more is within  $\pm 18$  (32) MeV/ $c^2$  of the  $\pi^0$  ( $\eta$ ) mass. These correspond to  $\pm 3\sigma$  windows, where  $\sigma$  is the mass resolution. This set of criteria is referred to as the  $\pi^0/\eta$  veto. For the primary photon, we sum the energy deposited in arrays of  $3 \times 3$  cells and  $5 \times 5$  cells around the maximum energy ECL cell; if their ratio is less than 0.95, the event is vetoed.

Charged pions and kaons are reconstructed as tracks in the CDC and SVD. Each track is required to have a momentum greater than 100 MeV/ $c$  and closest approach to the run-averaged interaction point within 2 cm in radius and  $\pm 5$  cm along the  $z$ -axis, aligned opposite the positron beam. We do not use the track to form the signal candidate if, when combined with any other track, it forms a  $K_S^0$  candidate with a mass within  $\pm 10$  MeV/ $c^2$  around the nominal  $K_S^0$  mass and a displaced vertex that is consistent with a  $K_S^0$ . We determine the pion ( $L_\pi$ ) and kaon ( $L_K$ ) likelihoods from the ACC response, specific ionization

$(dE/dx)$  in the CDC and TOF flight-time measurements for each track, and form a likelihood ratio  $\mathcal{L}_{\pi/K} = L_\pi/(L_\pi + L_K)$  to separate pions and kaons. We require  $\mathcal{L}_{\pi/K} > 0.85$  for pions, which gives an efficiency of 89% for pions and misidentification probability of  $\sim 10\%$  for kaons. For the  $\omega\gamma$  mode, we relax the requirement to  $\mathcal{L}_{\pi/K} > 0.8$ , which gives an efficiency of 94% for pions. (For kaons in the  $K^*\gamma$  modes, we require  $\mathcal{L}_{\pi/K} < 0.4$ , which gives an efficiency of 76–80%.) In addition, we remove pion and kaon candidates if they are consistent with being electrons based on ECL,  $dE/dx$  and ACC information, or consistent with muons based on KLM information.

Neutral pions are formed from two photons with invariant masses within  $\pm 10$  (16) MeV/ $c^2$  of the  $\pi^0$  mass, corresponding to a  $\sim 2\sigma$  ( $\sim 3\sigma$ ) window for  $\rho^-\gamma$  and  $K^{*-}\gamma$  ( $\omega\gamma$ ) modes. The photon momenta are then recalculated with a  $\pi^0$  mass constraint. We require each photon energy to be greater than 30 MeV. We also require the CM momentum of the  $\pi^0$  to be greater than 0.5 GeV/ $c$  for the  $\rho^-\gamma$  and  $K^{*-}\gamma$  modes.

Invariant masses for the  $\rho$  and  $\omega$  candidates are required to be within windows of  $\pm 150$  MeV/ $c^2$  ( $1\Gamma$ ) and  $\pm 30$  MeV/ $c^2$  ( $3.5\Gamma$ ), respectively, around their nominal masses, where  $\Gamma$  is the natural width of each resonance.

We form  $B$  candidates by combining a  $\rho$  or  $\omega$  candidate and the primary photon using two variables: the beam-energy constrained mass  $M_{bc} = \sqrt{(E_{beam}^*/c^2)^2 - |p_B^*/c|^2}$  and the energy difference  $\Delta E = E_B^* - E_{beam}^*$ , where  $p_B^*$  and  $E_B^*$  are the measured CM momentum and energy, respectively, of the  $B$  candidate, and  $E_{beam}^*$  is the CM beam energy. The magnitude of the photon momentum is replaced by  $(E_{beam}^* - E_{\rho/\omega}^*)/c$  when the momentum  $p_B^*$  is calculated. To optimize the event selection, we count Monte Carlo (MC) events in the region  $-0.10$  GeV  $< \Delta E < 0.08$  GeV and  $5.273$  GeV/ $c^2$   $< M_{bc} < 5.285$  GeV/ $c^2$ . We choose the selection criteria to maximize  $N_S/\sqrt{N_B}$ , where  $N_S$  is the expected signal yield in this region assuming the branching fractions to be the SM value in Ref. [3], and  $N_B$  is the expected background yield in the same region.

The dominant background arises from continuum events ( $e^+e^- \rightarrow q\bar{q}(\gamma)$ ) where the accidental combination of a  $\rho$  or  $\omega$  candidate with a photon forms a  $B$  candidate. We suppress this background using an event shape discriminator  $\mathcal{F}$ , the  $B$  candidate polar angle  $\theta_B^*$  in the CM frame, the vertex separation  $\Delta z$ , and the output of the  $B$ -flavor tagging algorithm:

1. The event shape discriminator  $\mathcal{F}$  [8] is a Fisher discriminant [9] constructed from 16 modified Fox-Wolfram moments [8, 10] and the scalar sum of the transverse momentum of all charged tracks and photons.
2. True  $B$  mesons follow a  $1 - \cos^2 \theta_B^*$  distribution in  $\cos \theta_B^*$ , while candidates in the continuum background are uniformly distributed.
3. In about 85% of events for the  $\rho^0\gamma$  and  $\omega\gamma$  modes, a fit can be successfully performed to determine the decay vertex of the candidate  $B$  meson as well as the origin of the remaining tracks in the event. The separation  $\Delta z$  between these two vertices along the  $z$ -axis discriminates between continuum events, which have a common vertex, and signal events, whose decay vertices are displaced.
4. The  $B$ -flavor tagging algorithm described in Ref. [11] returns the flavor of the other  $B$  meson ( $q = \pm 1$ ), and a tagging quality  $r$  ( $0 < r < 1$ ) which indicates the level of confidence in the flavor determination. The algorithm uses the particles in the event that are not associated with the signal  $B$  candidate, and provides additional

discrimination between signal, and continuum background where no true  $B$  meson is present.

For each of the quantities  $\mathcal{F}$ ,  $\cos\theta_B^*$  and  $\Delta z$ , we construct one-dimensional likelihood distributions for signal and continuum. Signal distributions are modeled with an asymmetric Gaussian function for  $\mathcal{F}$ ,  $\frac{3}{2}(a_0 - a_2 \cos^2 \theta_B^*)$  for  $\cos\theta_B^*$ , and an exponential convolved with a Gaussian resolution function for  $\Delta z$ ; continuum background distributions are modeled with an asymmetric Gaussian function for  $\mathcal{F}$ ,  $(b_0 - b_2 \cos^2 \theta_B^*)$  for  $\cos\theta_B^*$ , and a sum of three Gaussian functions with a common mean for  $\Delta z$ ; the coefficients  $a_0, a_2, b_0$  are close to unity while the coefficient  $b_2$  is close to zero.

Since  $\mathcal{F}$ ,  $\cos\theta_B^*$  and  $\Delta z$  are independent quantities, we form a likelihood ratio  $\mathcal{R} = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_c)$  to combine them, where  $\mathcal{L}_s$  and  $\mathcal{L}_c$  are products of  $\mathcal{F}$ ,  $\cos\theta_B^*$  (and  $\Delta z$  if available) likelihood distributions for signal and continuum, respectively. The likelihood distribution for the background  $\Delta z$  distribution is determined from data in the sideband region  $5.20 \text{ GeV}/c^2 < M_{bc} < 5.24 \text{ GeV}/c^2$ ,  $|\Delta E| < 0.3 \text{ GeV}$ ; all the other likelihood distributions are determined from MC samples.

We determine the  $\Delta z$  likelihood function separately for the two datasets as the vertex resolution is improved in the SVD2 with respect to the SVD1. As a consequence, we introduce two sets of likelihood ratios and selection criteria for each decay mode.

On the plane defined by the tagging quality and likelihood ratio,  $(r, \mathcal{R})$ , signal tends to populate the edges at  $r = 1$  and  $\mathcal{R} = 1$ ; continuum tends to populate the edges at  $r = 0$  and  $\mathcal{R} = 0$ . We select the events in a signal enriched region defined by  $\mathcal{R} > \mathcal{R}_1$  for  $r > r_1$ , and  $\mathcal{R} > 1 - \alpha(1 + r)$  for  $r_2 < r < r_1$ , where the parameters  $r_1$ ,  $r_2$ ,  $R_1$  and  $\alpha$  are mode dependent and are determined so that  $N_S/\sqrt{N_S + N_B}$  is maximized (we use this quantity instead of  $N_S/\sqrt{N_B}$  because of the limited statistics of the MC simulation sample that is used in this procedure). The values are  $r_1 = 0.85$ ,  $r_2 = 0.01$ ,  $R_1 > 0.8$  and  $\alpha = 0.025$  for the  $\rho^0\gamma$  mode in the first subset of data; similar values are used for the other subset and for the  $\rho^-\gamma$  and  $\omega\gamma$  modes. We define the rest of the area as the background enriched region.

We consider the following  $B$  decay backgrounds:  $B \rightarrow K^*\gamma$ , other  $B \rightarrow X_s\gamma$  processes,  $B \rightarrow \rho\pi^0$  and  $\omega\pi^0$ ,  $B \rightarrow \rho\eta$  and  $\omega\eta$ ,  $B^- \rightarrow \rho^-\rho^0$ , other charmless  $B$  decays, and  $b \rightarrow c$  backgrounds. We find the  $b \rightarrow c$  background to be negligible. The  $B \rightarrow K^*\gamma$  background may mimic the signal decay  $B \rightarrow \rho\gamma$  if the kaon from  $K^*$  is misidentified as a pion. In order to further suppress  $B \rightarrow K^*\gamma$ , we calculate  $M_{K\pi}$ , where the kaon mass is assigned to one of the pion candidates, and reject the candidate if  $M_{K\pi} < 0.96$  (0.92)  $\text{GeV}/c^2$  for the  $\rho^0\gamma$  ( $\rho^-\gamma$ ) mode. The decay chain  $\bar{B}^0 \rightarrow \bar{K}^{*0}\gamma$ ,  $\bar{K}^{*0} \rightarrow K_S^0\pi^0$ ,  $K_S^0 \rightarrow \pi^+\pi^-$  has the same final state as  $\bar{B}^0 \rightarrow \omega\gamma$ , and has a small contribution due to the tail of the  $K^*$  Breit-Wigner line shape. In addition,  $B \rightarrow K^*\gamma$  and other  $B \rightarrow X_s\gamma$  decays contribute to the background when the  $\rho$  and  $\omega$  candidates are selected from a random combination of particles. Charmless decays with a  $\pi^0$  or  $\eta \rightarrow \gamma\gamma$ ,  $B \rightarrow \rho\pi^0$ ,  $\omega\pi^0$ ,  $\rho\eta$  and  $\omega\eta$ , may mimic the signal if one of the photons from  $\pi^0$  or  $\eta$  decay is soft and undetected by the  $\pi^0/\eta$  veto condition. To suppress this background, we calculate the cosine of the helicity angle  $\theta_{\text{hel}}$ , and reject the candidate if  $|\cos\theta_{\text{hel}}| > 0.8$  (0.6) for the  $\rho^0\gamma$  and  $\omega\gamma$  ( $\rho^-\gamma$ ) modes. Here,  $\theta_{\text{hel}}$  is defined as the angle between the  $\pi^+$  and  $B$  momentum vectors in the  $\rho$  rest frame, or the angle between the normal to the  $\omega$  decay plane and the  $B$  momentum vector in the  $\omega$  rest frame. The decay  $B^- \rightarrow \rho^-\rho^0$ ,  $\rho^- \rightarrow \pi^-\pi^0$  also contributes to the  $B^0 \rightarrow \rho^0\gamma$  mode when both one pion from the  $\rho^-$  decay and one photon from the  $\pi^0$  decay are soft and undetected. The other charmless decays have small contributions and are considered as an additional background component when we extract the signal yield.

The reconstruction efficiency for each mode is defined by the fraction of the signal yield remaining after all selection criteria, where the signal yield is determined from an unbinned maximum likelihood fit to the MC sample. The signal distributions are modeled as the product of a Gaussian function for  $M_{bc}$  and an empirical function known as the Crystal Ball line shape [12] to reproduce the asymmetric ECL energy response for  $\Delta E$ . The background component is modeled as the product of a linear function for  $\Delta E$ , and an ARGUS function [13] for  $M_{bc}$ . From the fit, we find efficiencies of about 5% as listed in Table I. The systematic error on the efficiency is the quadratic sum of the following contributions estimated from control samples: the photon detection efficiency (2.2%), measured from radiative Bhabha events; charged tracking efficiency (1.0% per track) from partially reconstructed  $D^{*+} \rightarrow D^0\pi^+$ ,  $D^0 \rightarrow K_S^0\pi^+\pi^-$ ,  $K_S^0 \rightarrow \pi^+(\pi^-)$ ; charged pion identification (1.0% per pion) from  $D^{*+} \rightarrow D^0\pi^+$ ,  $D^0 \rightarrow K^-\pi^+$ ; neutral pion detection (4.6–7.3%) from  $\eta$  decays to  $\gamma\gamma$ ,  $\pi^+\pi^-\pi^0$  and  $3\pi^0$ ;  $\mathcal{R}$ - $r$  and  $\pi^0/\eta$  veto requirements (5.4%) from  $B^- \rightarrow D^0\pi^-$ ,  $D^0 \rightarrow K^-\pi^+$ ; and MC statistics (0.9–1.5%).

We perform an unbinned maximum likelihood fit to the data in the  $(M_{bc}, \Delta E)$  fit region bounded by  $|\Delta E| < 0.3$  GeV and  $M_{bc} > 5.2$  GeV/c<sup>2</sup>, simultaneously for the three signal modes (collectively referred to as  $B \rightarrow (\rho, \omega)\gamma$ ) and the two  $B \rightarrow K^*\gamma$  modes. We fit the two data subsets simultaneously, so that in total ten distributions are included in the fit. We define the combined branching fraction  $\mathcal{B}(B \rightarrow (\rho, \omega)\gamma) = \mathcal{B}(B^- \rightarrow \rho^-\gamma)$ , assuming the isospin relation [14]  $\mathcal{B}(B^- \rightarrow \rho^-\gamma) = 2\frac{\tau_{B^+}}{\tau_{B^0}}\mathcal{B}(\overline{B}^0 \rightarrow \rho^0\gamma) = 2\frac{\tau_{B^+}}{\tau_{B^0}}\mathcal{B}(\overline{B}^0 \rightarrow \omega\gamma)$ , where we use  $\frac{\tau_{B^+}}{\tau_{B^0}} = 1.086 \pm 0.017$  [16]. We also assume  $\mathcal{B}(B \rightarrow K^*\gamma) \equiv \mathcal{B}(B^- \rightarrow K^{*-}\gamma) = \frac{\tau_{B^+}}{\tau_{B^0}}\mathcal{B}(\overline{B}^0 \rightarrow \overline{K}^{*0}\gamma)$ .

We describe the events in the fit region using a sum of the signal, continuum,  $K^*\gamma$ , and other background hypotheses. Parameters of the signal description for  $M_{bc}$  are calibrated using  $B^- \rightarrow D^0\pi^-$  samples. Those for  $\Delta E$  are calibrated using the result of a fit to the  $\Delta E$  distribution of the  $B \rightarrow K^*\gamma$  control sample, in which the mean and the width are allowed to float. We use the branching fractions for  $B \rightarrow (\rho, \omega)\gamma$  and  $B \rightarrow K^*\gamma$  as the free parameters, from which the signal yield for each channel is deduced using the efficiency for each mode. We assume the efficiency systematic errors are fully correlated when we evaluate the systematic error. The continuum background is modeled as the product of a linear function for  $\Delta E$  whose slope is allowed to float, and an ARGUS function for  $M_{bc}$  whose parameters are fixed from a comparison between data and MC in the background enriched region and MC in the signal enriched region. The continuum contribution in the data sample is allowed to float. The size of the  $K^*\gamma$  background component in each  $(\rho, \omega)\gamma$  channel is constrained using the fit to the  $K^*\gamma$  events. The contributions of the other backgrounds are fixed using known branching fractions or upper limits. The free parameters in the fit are therefore the branching fractions for  $B \rightarrow (\rho, \omega)\gamma$  and  $B \rightarrow K^*\gamma$ , five continuum fractions, and five continuum  $\Delta E$  slopes.

We also perform individual fits to the three signal modes and the two  $B \rightarrow K^*\gamma$  modes. The two data subsets are fitted simultaneously for each mode. The size of the  $\overline{K}^{*0}\gamma$  background in the  $\rho^0\gamma$  mode and  $K^{*-}\gamma$  background in the  $\rho^-\gamma$  mode are fixed according to the fit results to the  $B \rightarrow K^*\gamma$  modes and the known particle misidentification probabilities. The free parameters in each fit are the signal yield, the continuum fraction, and the continuum  $\Delta E$  slope.

Results of the simultaneous fit are shown in Fig. 2 and given in Table I. The simultaneous fit gives a significance of 1.9 standard deviations, where the significance is calculated as

$\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\max})}$ , and  $\mathcal{L}_{\max}$  ( $\mathcal{L}_0$ ) is the maximum likelihood from the fit when the signal branching fraction is floated (constrained to be zero). In order to include the effect of possible systematic error in the significance calculation, we change each parameter by one standard deviation in the direction that gives the smallest resulting significance. The systematic error in the signal yield is estimated by varying each of the fixed parameters by its standard deviation, and then taking the quadratic sum of the deviations in the signal yield from the nominal value. The combined branching fraction is  $\mathcal{B}(B \rightarrow (\rho, \omega)\gamma) = (0.72^{+0.43}_{-0.39}{}^{+0.28}_{-0.27}) \times 10^{-6}$ , where the first and second errors are statistical and systematic, respectively.

Since the significance is small, we quote a 90% confidence level upper limit  $\mathcal{B}_{90}$  using the relation  $\int_0^{\mathcal{B}_{90}} \mathcal{L}(x)dx = 0.9 \int_0^\infty \mathcal{L}(x)dx$ , where  $\mathcal{L}(x)$  is the likelihood function with the branching fraction fixed at  $x$ . The systematic error is taken into account assuming a Gaussian distribution. We find

$$\mathcal{B}(B \rightarrow (\rho, \omega)\gamma) < 1.4 \times 10^{-6} \quad (1)$$

at the 90% confidence level. Results of the fits to the individual modes are also given in Table I.

A similar fit procedure is performed by using the ratio of branching fractions  $\mathcal{B}(B \rightarrow (\rho, \omega)\gamma)/\mathcal{B}(B \rightarrow K^*\gamma)$  instead of  $\mathcal{B}(B \rightarrow (\rho, \omega)\gamma)$ , so that the systematic error partially cancels. We find  $\mathcal{B}(B \rightarrow (\rho, \omega)\gamma)/\mathcal{B}(B \rightarrow K^*\gamma) < 0.035$  at the 90% confidence level. One can use this result to constrain  $V_{td}$ : for example, using the prescription given in Ref. [15],

$$\frac{\mathcal{B}(B \rightarrow (\rho, \omega)\gamma)}{\mathcal{B}(B \rightarrow K^*\gamma)} = \left| \frac{V_{td}}{V_{ts}} \right|^2 \frac{(1 - m_{(\rho, \omega)}^2/m_B^2)^3}{(1 - m_{K^*}^2/m_B^2)^3} \zeta^2 [1 + \Delta R] \quad (2)$$

where the form factor ratio  $\zeta = 0.85 \pm 0.10$  and  $SU(3)$  breaking effect  $\Delta R = 0.1 \pm 0.1$ , we obtain  $|V_{td}/V_{ts}| < 0.21$  at the 90% confidence level. This limit is consistent with other determinations of  $|V_{td}/V_{ts}|$  [16].

In conclusion, we search for the  $b \rightarrow d\gamma$  process using a simultaneous fit to the  $B \rightarrow \rho\gamma$ ,  $\bar{B}^0 \rightarrow \omega\gamma$  and  $B \rightarrow K^*\gamma$  modes. The upper limit we obtain is already within the range of SM predictions [3, 4] and can be used to constrain  $V_{td}$ .

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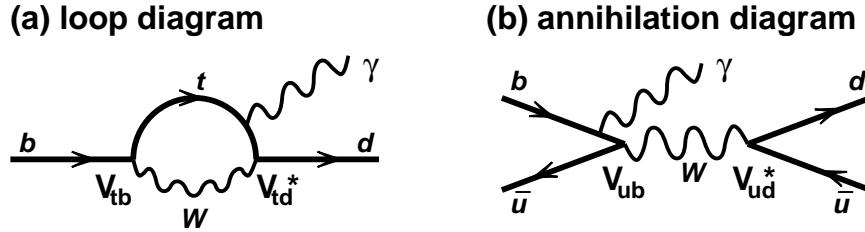


FIG. 1: (a) Loop diagram for  $b \rightarrow d\gamma$  and (b) annihilation diagram only for  $B^- \rightarrow \rho^-\gamma$ .

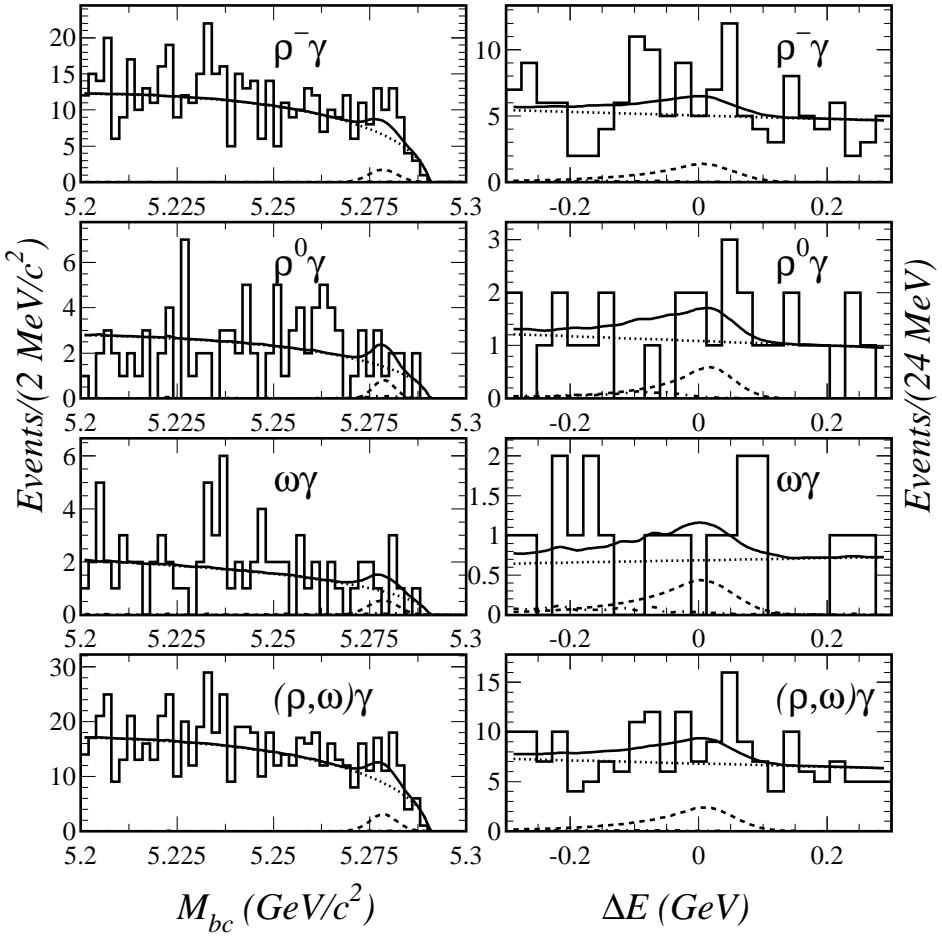


FIG. 2: Projections of the simultaneous fit results to  $M_{bc}$  (in the region  $-0.10 \text{ GeV} < \Delta E < 0.08 \text{ GeV}$ ) and  $\Delta E$  (in the region  $5.273 \text{ GeV}/c^2 < M_{bc} < 5.285 \text{ GeV}/c^2$ ) for the individual modes and the sum of them. Lines represent the total fit result (solid), signal (dashed), continuum (dotted), and  $B$  decay background (dot-dashed) components.

TABLE I: Efficiencies, significances, and 90% confidence level upper limits for the branching fractions.

Mode	Efficiency ( $\pm$ syst)	Significance	Upper limit (90% C.L.)
$B \rightarrow (\rho, \omega)\gamma$ combined	—	1.9	$1.4 \times 10^{-6}$
$B^- \rightarrow \rho^- \gamma$	$(5.5 \pm 0.4)\%$	2.1	$2.2 \times 10^{-6}$
$\bar{B}^0 \rightarrow \rho^0 \gamma$	$(3.9 \pm 0.3)\%$	0.6	$0.8 \times 10^{-6}$
$\bar{B}^0 \rightarrow \omega \gamma$	$(3.9 \pm 0.4)\%$	0.2	$0.8 \times 10^{-6}$